BEAMLOADING AND COMPENSATION

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What is beam loading?

Longitudinal focusing and acceleration are performed by RF electric fields confined(?) within cavity resonators. The topic of "Beam Loading" denotes all the phenomena encompassed by

> "the cavity is driven by two current sources: (i) the generator and (ii) the beam".

Typically the generator comprises 1 or 2 Fourier components, while the beam has many. We deal with a coupled system. One attempts to control the beam using the generator components; but our ability to control the generator is compromised by strong perturbations from the beam.

The longitudinal emittance and ellipse aspect ratio, and acceleration rate, dictates the voltage per turn. Qualitatively, from a control/stability perspective the system follows demand values when the generator current is greater than the beam current component. If this ideal beam-load ratio ($I_g/I_b \gg 1$) is not possible, then corrective mechanisms (such as vector feedback of the voltage or vector feedforward of beam current) are required.

The technical distinction made between feed-back and feed-forward is sometimes confusing to non-controls experts. Feed-back: use a measure of the quantity being controlled (e.g. gap voltage) as an input. Feed-forward: use some other quantity (e.g. beam current) for correction of the quantity being controlled.

The range of "beam loading" phenomena includes: steady-state phase and amplitude shift of voltage due to reactive beam-component (compensated by detuning), periodic transients (if empty buckets), injection/accumulation transients, coupled-bunch instabilities (due to fundamental and HOMs), and power-limited (i.e. Robinson) instability. A review of theory and state-of-art applications was given at 7th ICFA Mini-Workshop held at KEK-Tanashi in February 1998. See URLs: http://www.triumf.ca/people/koscielniak/beamload.htm and
http://www.triumf.ca/people/koscielniak/jhf_shane.htm
There was also some reporting of phenomena at 9th ICFA Mini-Workshop in Geneva
http://nicewww.cern.ch/PSdata/www/icfa9/ICFAWelcome.html

I shall speak mostly about developments since the 1998 workshop. Due to constraints of preparation time and limited personal knowledge, I have have identified only three areas.

- Introduction of Magnetic Alloy (e.g. Finemet) cores and adoption of low Q cavities.
- e^+e^- factories with very large beam current (e.g. KEKB, PEP II).
- Developments at p,p factories (e.g. LHC).

The reason to include e^+e^- in a talk ostensibly about proton machines is that lepton machines represent the present beamload frontier. The territoy pioneered and conquered by e^+e^- will be settled by future hadron machines (and would have been visited by SSC had it been built).

One other development is worthy of mention: the decision of the neutron-source type machines (SNS, ESS, etc.) to adopt full energy injection via a SC linac into a storage ring; thereby avoiding many of the beamload problems of rapid cycling synchrotrons.

MA-loaded Cavities

Historically, booster-type proton synchrotrons have used low RF (say, < 100 MHz); and, in addition, the fast-cycling machines have desired high acceleration gradients. Often these machines have used lower RF (i.e. long bunches) as a means of reducing space-charge effects. Low frequency structures are traditionally loaded with material of high relative permeability (such as ferrite) so as to shorten them (dramatically) compared with the free-space wavelength.

At yet lower RF (say, < 10 MHz) micro-grained magnetic alloys have been considered as an alternative to (parallel bias) ferrites since *circa* 1995. Impetus mostly from the JHF team, Refs[1,2,4,6]. The advantages/disadvantages of these materials are tightly coupled, and listed as follows (in rough order of importance).

Shunt resistance independent of RF flux density

The shunt resistance of a coaxial resonator is given by the formula

$$R_{\text{shunt}} = \text{length} \times \ln\left[\frac{OD}{ID}\right] \times \mu Q f \qquad \begin{array}{c} OD = \text{outside diameter} \\ ID = \text{inside diameter} \end{array} \tag{1}$$

For FT3M (FineMet), when excited in the range of a few MHz, the product of permeability and quality factor and drive frequency, $\mu \times Q \times f$, remains constant up to high magnetic flux (2kGauss) whereas for Ni-Zn ferrites (e.g. 4M2, N5C, SY2) the product falls quickly for RF magnetic fields above 100 Gauss. Consequently, much higher RF fields may be sustained leading to higher effective gradient (gap voltage/cavity length).

For Ni-Zn ferrite the gradient limited to 15-20 kV/m.

FineMet is limited by power-density/air-cooling considerations of < 4 W/cm^3 to a gradient of 50 kV/m. If water cooling is provided then can go to 10 W/cm^3, but the structure length increases (mechanical and dielectric reasons) and gradient falls below 100 kV/m.

Small shunt resistance

For RF fields below 100 Gauss, the $\mu Q f$-product of MA is roughly 10 times smaller than for ferrite. This is because the intrinsic quality factor is very low; the material is lossy. Consequently, though higher gradient may be obtained, the shunt resistance is small c.f. ferrite and the power consumption is high. As a corollary the generator current is comparatively large, which is beneficial to beam loading.

High Curie temperature

The high Curie temperature (≈ 570 °C) allows to operate this material at high field despite the high losses and high heat dissipation.
In test, characteristics of cores remained constant at 170 °C.

Longitudinally compact structures

Finemet is in the form of a amorphous metallic tape which can be wound into a core over 1 m in diameter. C.f. $\ln(OD/ID)$ term in R_{shunt}. A silica coating is used as insulator. Contrarily, ferrite is ceramic in nature and is manufactured by baking in an oven. Therefore large ferrite cores are difficult to produce.

The approximately 10 times higher (than ferrite) relative permeability of MA may allow for even more compact structures. However, relative permeability of MA drops above 2 MHz, or if cut-cores are used above 8 MHz. Whereas the ferrites can operate at up to 100 MHz.

Tuner not required

The intrinsic Q-value of the MA core is 0.6-1. The low quality factor implies the resonance is broad. This has, in principle, several benefits. Cavity has no need of a tuning loop even when the drive frequency spans a large range of $\beta = v/c$. Cavity has no need of a d.c. power supply for the "magnetic biasing field". It is not necessary to detune the cavity to compensate steady-state beam-loading. Potential for system simplification and reduced costs.

Change of Q

The Q-value of the core can be changed by more than 10 by introducing a radial gap (J. Griffin suggestion). Thus R/Q value of the cavity is variable without changing shunt resistance. Beneficial regarding periodic beamloading (e.g. JHF 50 GeV synchrotron) where it is desirable to have low R/Q.

Reduced CB instability

There are probably few (if any) high-Q HOMs; none below 30 MHz. The cavity is wide-band (it does not "ring") and has little memory of the beam which has passed through it, and so cannot communicate coupled-bunch instabilities from one bunch to the next.

Disadvantage: the broad resonance may span several revolution harmonics and hence there is beam induced voltage at several harmonics, e.g. JHF 3 GeV synchrotron. Fortunately, the shunt resistance is small and the voltages are small enough to be compensated by a 1-turn delay feedforward of the beam current components from a diagnostic monitor. But there is a cost, here, in terms of complexity.

Transient beam-loading

Injection transients may, in principle, lead to emittance growth during the time that the fields-and-bunches stabilize to give the periodical transients. When there are gaps in the beam, the spectrum of injection and periodic transients becomes richer. The periodical transients are only an issue if there are to be transfers between machines, or collisions of counter-rotating beams. But a single beam accelerated only in a single ring sees no detrimental effect from a small modulation of phase and amplitude.

When there are ring-to-ring transfers, the best policy is impedance matching between rings. Unfortunately, this is rarely possible by passive means; and so voltage-feedback and beam-feedforward are used. With the classical high-Q cavity (i.e. low R/Q) the transients take a long time to build up or (die away) but they are small perturbations. Regarding the use of MA-loaded cavities, the low-Q reduces the duration of injection/dynamical transients; but the broad-resonance may imply strong beam-induced voltage at revolution or RF harmonics. The MA-loaded cavity does, however, have the advantage of eliminating the transient response of the tuner from the confusion. Careful analysis is required, case by case.

Barrier bucket

It is claimed that low Q is suited to production of a pulsed sinusoid for barrier bucket manipulations. As applied in the BNL AGS, this operation is contrary to requirements for beam loading. Beam-loading ideal is low R/Q, which implies large generator current (small R) and large stored energy (large Q). If, however, you wish to form a barrier using small generator $I_g = (V/R)[Q + \sin \omega t]$ then large R and small Q is desired. Use of MA gives low Q.

In the BNL AGS test of MA, Ref[3], the waveform was not as advertized; there is a predictable asymmetric overshoot (is Q=0.6 too large?). One also needs beam feed-forward to compensate beam Fourier components. Overshoot can be reduced by using more generator harmonics, but this adds to system complexity.

Multi-harmonic RF

Dual (1st & 2nd) harmonic RF with a single cavity for space-charge reduction. (demonstrated at HIMAC and WERC).
Dual (1st & 3nd) harmonic RF with a single cavity for sawtooth waveform for bunch compression (proposed/simulated for NIRS).

Practical demonstrations

97 JHF: operated cavity with 10 kV, 30 kW, Q=0.6, R=83 ohm.

98 JHF: bench testing Q=1, R/Q=600 ohm resonator. Q value increased by introducing radial gap and bench testing Q=10, R/Q=60ohm run at 20 kV (amplifier limitation).

99 BNL AGS Barrier cavity with Q=0.6, R/Q=1500 ohm, $f_{\rm res} = 1$ MHz, 10kV/gap and 4 gaps developed total 40 kV. Employed 1-turn delay feedforward to compensate beam-induced voltages at 1st,2nd,3rd harmonics. For comparison, tests with ferrite cavity Q=30, R/Q=180, R=5400, $f_{\rm res} = 2.6$ MHz, shows barrier is distorted by “ringing”.

HIMAC (medical m/c) accelerated light ions through a huge frequency change 1-8 MHz, with gradient 50 kV/m. Also demonstrated dual harmonic (1st & 2nd).

Round-up

When I made the beam-load review at 7th ICFA workshop, the JHF group had proposals for MA-loaded cavities, but made no demonstration. Since that time, there has been an explosion of activity led by the JHF group and several MA-cavities working in machines (KEK PS, AGS, HIMAC, NIRS, Wakasawan ERC) have demonstrated that both the high effective gradients and the large frequency swings are achievable in reality.

There are definitely niches (e.g. FFAGs) where the MA-loaded type of cavity has definite advantages over parallel biased ferrites, but their use is not a panacea as sometimes claimed. Given the close coupling of benefits and detractions, careful anlaysis has to be made for each particular application. A very careful comparison of "Finemet versus Ferrite - Pros & Cons" (K.Y. Ng, 1999 PAC) is worth reading. For example, despite low RF, the lack of frequency swing led SNS to choose 4M2 ferrites for its 1st & 2nd harmonic RF systems, Ref[5].

It is dangerous to generalise, but it is the authors personal opinion that MA-loaded cavities are suited to LF applications involving

- requirement for high effective gradient
- large frequency swing, or
- large beam load ratio (Ib/Ig), i.e. beam power dominates consumption
- avoidance of coupled bunch instabilities

However, these benefits may come at the cost of higher power (c.f. ferrite loaded cavity) and or requirement to compensate beam Fourier components (if ring is not full) by multi-harmonic feed-forward. For example JHF 3GeV PS uses 400 kW to generate 40 kV.

Do not forget perpendicular bias ferrite. Though last reported in 1994, this material (yttrium garnet) still has the property to be operated in magnetic saturation giving both high electric and magnetic Qs. Cavities with these materials have R/Q well suited to beamloading applications. However, tuning circuits for these cavities are complex.

References

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Ref[2] "New type of RF cavity for high intensity proton synchrotron using high permeability magnetic alloy", 98 EPAC.
Ref[3] "Barrier cavities in the Brookhaven AGS", 99 PAC
Ref[4] "Accelerator Complex for the Joint Project of KEK/JHF and JAERI/NSP", 99 PAC.
Ref[5] "Ring RF and Longitudinal dynamics in the SNS", 2000 EPAC.
Ref[6] "RF Acceleration Systems for the Joint Project", 2000 EPAC.

e^+e^- Colliders for factories

We have just considered machines where coupled-bunch (CB) instabilities can be avoided; we move now to machines where they are guaranteed. The B-Factory proposals (KEKB, PEP-II) date from *circa* 1992 and have some features in common with the p,p collider LHC. Factory machines absolutely require beam-loading compensation, <u>and</u> Higher Order Mode (HOM) damping, <u>and</u> coupled-bunch (CB) feedbacks for their operation. There was significant R&D performed in 94-96 and preliminary commissioning (low current) of beams in July 1998. At the time of the 7th ICFA Mini-workshop, February 1998, it was not known whether the very complex RF and F/B systems would deliver desired performance. (Effectiveness of the CB feedbacks had been demonstrated at DAΦNE and ALS.) I am happy to remind you that beam currents approaching design values were achieved in 1999 (PEP-II) and 2000 (KEKB), Refs[5,6].

As a generality, KEKB has taken a strategy of passive measures (use of SCC and ARES cavities) to combat the usual beamload problems, whereas PEP-II adopted active measures using multiple-level cavity feedbacks relying heavily on digital electronics. The full difficulty of setting up all the cavity loops, adjusting the group delays, nulling out the steady-state phase offsets of cables and of bunch positions (modulated by periodic transients) compared with references, can be appreciated from reading of Ref[1]. Some of the "datum" problems in "active measures" are also encountered in bunch-by bunch F/B, Ref[4]. Perhaps, the multi-laboratory collaboration (SLAC-LBL-INFN) to provide CB damping systems for ALS, SPEAR, PEP, DAΦNE, etc., gave them confidence to pursue that strategy.

As a generality, KEKB and PEP-II have chosen different strategies for the implementation of CB F/B electronics. For example, KEKB have used direct sampling and simple 2-tap FIR filters, whereas PEP-II has used down-sampling, more sophisticated 3-tap FIR and assigned several bunches per processor.

No doubt, future e^+e^- ring-colliders will combine passive and active measures to attain yet higher beam current and luminosity.

Beam-loading aspects

We take our list of topics from the review "RF Issues for High Intensity Factories" by K. Akai in EPAC 96 . As we shall see, the severity of several beam-load phenomena is proportional to beam-loading ratio $Y = I_b/I_g$ and inversely proportional to Q-factor.

Instability driven by the accelerating mode

Detuning of the cavity for steady-state compensation of the reactive component of beam-loading automatically stabilizes the m=0 CB-mode. However, if the revolution frequency is comparable with the frequency detuning, then low order CB-modes with large growth rates may be excited. The detuning is $\Delta f \propto Y/Q$. There are two strategies to tame this instability.

- Cavity with large stored energy. A Super-Conducting (SC) cavity operated at high voltage is one solution, e.g. KEKB SCC. Another solution is the Normal Conducting (NC) ARES: a 3-cavity system where an accelerating cavity is resonantly coupled with a large energy storage cavity operating in a high-Q mode, Ref[0]. R/Q of the fundamental is reduced to 15 ohm. and the required detuning reduced to 10 kHZ c.f. the 99 kHZ revolution frequency. If necessary, a narrowband CB-feedback for identified modes may be added to the LER.

- A 1-turn delay comb filter feedback at revolution harmonics. The tines (teeth) of the comb (see LHC discussion) are narrowband and each spans twice the synchrotron frequency. e.g. PEP-II comb filter F/B gives up to 17dB impedance reduction across 30 revolution harmonics. Note, direct vector feedback does not change the detuning condition, and the broadening of the resonance may even exacerbate the problem.

Bunch Gap Transient

In order to avoid ion-trapping, and to allow for abort kicker rise time, a 5% gap is introduced into the bunch trains of PEP-II and KEKB. This periodic transient causes phase (and amplitude) modulation of the RF train. In B-factories, this modulates the IP reducing luminosity. Having corresponding gaps in electron and positron bunch trains partially compensate the effect, but additional methods are needed. The modulation is proportional Y/Q.

In KEKB, the problem is addressed with large stored energy (i.e. high-Q) by the use of SC and the ARES NC cavities. The use of ARES in LER yields $\Delta V/V = 0.8$% and $\Delta\phi = 2.6$ deg which is acceptable. A disadvantage of the ARES [Accelerator Resonantly coupled with an Energy Storage] system is the need to tune 3 cavities and to adjust the coupling between them, which leads to quite complicated servo-loops and complicated tuning-dynamical response. However, proponents claim this gives more operational flexibility.

In PEP-II, the phase modulation causes difficulty for both the cavity feedbacks, and for the CB F/B system. Essentially the problem is that these are steady state offsets which must be rejected from the feedbacks. For the cavity system, one must avoid trying to correct the transient; and for the CB F/B one must avoid "kicking" bunches which are apparently displaced, but actually sitting at equiliubrium positions. The gap-voltage feed-forward module Ref[2], a master-piece of control engineering, generates reference phases using an adaptive algorithm implemented on a DSP. Without this reference the direct vector feedback would drive the klystron into saturation.

Robinson power-limited instability

When the cavity is driven more strongly by the beam current than the generator current, one losses control of the RF system. The factories operate in a regime I_b/I_g equal from 2 to 5, where there is only a small stability margin. To combat this instability, a direct vector feedback (of the gap voltage) is used to give an impedance reduction of the fundamental resonance. e.g. KEKB SSC cavity. DAΦNE uses a solid-state driver and then klystron with loop gain 27dB and delay 350ns. PEP-II NC cavities uses a wideband analogue system giving a 15dB impedance reduction.

NC versus SC

Severity of many beam-loading effects (e.g. transients, m=0 CB instability) is proportional to $Y/Q = (I_b/V)(R/Q)$. Consequently, when considering Normal Conducting (NC) cavities one usually favours low R/Q. High Q implies large stored energy. Large R means that both beam and generator could induce large voltages. However, R/Q is not the whole story, voltage V is also relevant. Super-Conducting (SC) cavities typically have high R/Q and can sustain very high field gradients allowing large gap voltages (this is what makes them economically attractive). These high voltages, which imply large stored energy thus reducing the effects of transients, allow one to use few cavities and lower the machine impedance compared with NC cavities. Further, the possibility to operate with large voltages implies the possibility for the generator current to overcome the beam current. The KEKB SSC has R/Q=93 ohm, $Q = 8.9 \times 10^4$, R=8.3 Mohm, and power coupler rated at 500 kW. One disadvantage of conventional SC cavities with Qs of 10^8 or higher is that tuning must be very precise, made challenging by thermal and acoustical phenomena. But this is less of an issue for the open-type single-mode cavity.

High-power handling

The beamload ratio is reduced when there are a small number of cavities with large voltages. Consequently, each cavity should provide several hundred kW of beam power. This challenges the thermal and electrical performance of input couplers, RF windows, etc., and also the junction between cavity and HOM waveguides, and the absorbers which may out-gas. Despite successes, this is an area where more R&D is still needed. See H. Padamse, Ref[3].

Summary table

Quantity	PEP-II		KEKB	
RF (MHz)	476		509	
# bunches	1658		5000	
harmonic #	3492		5120	
Ring	LER	HER	LER	HER
I_b design (A)	2.16	0.75	2.6	1.1
I_b actual (A)	.680	.354	.065	.013
$V_{\rm gap}$ (MV)	.86	.7	.5	1.8 and .5
$P_{\rm tot}$ (kW)	413	256		
Type	NC	NC	ARES	ARES and SCC
# of	6	20	20	12 and 8
HOM power (MW)	0.23	0.15	0.57	0.14
beam power (MW)	1.85	3.73	4.5	4.0
beamload problem			Cures	
Robinson		direct F/B	ARES	direct F/B on SCC
m=-1,-2..		Comb filter	ARES	SCC and ARES
transient	direct F/B and GVFFM		ARES	SCC and ARES

Alternate buckets filled in PEP, consecutive buckets filled in KEKB.

References

Ref[0] "The ARES cavity for the KEK B-factory", 96 EPAC.

Ref[1] "Commissioning Experience with the PEP-II Low-Level RF System", 97 PAC
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Ref[3] "Review of Experience with HOM Damped Cavities", 98 EPAC.
Ref[4] "Multi-bunch longitudinal dynamics abd diagnostics via a digital feedback system at PEP-II, DAΦNE, ALS and SPEAR", 98 EPAC
Ref[5] "Commissioning results of the KEKB and PEP-II B-factories", 99 PAC.
Ref[6] "Commissioning of the KEKB RF system", 2000 EPAC.

Coupled-bunch aspects

The current strategy to achieve high luminosity for high energy physics experiments (as well as in high brilliance in synchrotron radiation sources) is to store huge currents distributed in many bunches in circular machines. The interaction of these bunches with high-Q resonators (i.e. the RF system) would limit the current to rather low values because of coupled bunch instabilities. To overcome this problem two measures are adopted:

- The impedance of parasitic cavity modes (HOMs) is reduced substantially
- Feedback systems are applied to stabilize the beam.

There are two requirements for a successful feedback

- growth rates of CB modes that are not damped by feedback must not exceed radiation or Landau damping.
- the coherent frequency shifts must be smaller than the synchrotron frequency, else there is mode-coupling (turbulence).

These requirements define an upper bound for the HOM impedance.

HOM damping

Parasitics must be reduced typically below 1 kohm/cavity and the Q-value damped below 100; which is two orders of magnitude lower than was achieved with antenna-type HOM couplers. Note by "multi-mode" we shall refer to a cavity with nose cones to increase the $R_{\rm shunt}$ of the fundamental mode; whereas "single-mode" refers to a cavity with a non re-entrant geometry and wide iris openings. Three methods are used to propgate HOM EM field energy into broad-band absorber loads

1. "single-mode" single-cell cavity with widely opened beam pipe such that HOMs are above the pipe cutoff. This allows for a simple structure, but lowers shunt resistance. Absorbers are coaxial with the pipe. e.g. KEKB single-cell SC Cavity 15 kW dissipation, CESR-B SC cavity.
2. "multi-mode" single-cell cavity loaded with waveguides having cut-off frequencies above the fundamental. e.g. PEP-II NC single-cell cavity uses 3 rectangular waveguides. Fundamental has R/Q=117 ohm, Q=14000, HOMs have R< 1 kohm with variety of R/Q.

3. cavity with coaxial (or radial) transmission line, having a notch filter to reject the fundamental. e.g. KEKB ARES

The HOM absorbers must typically handle 10 kW/cavity. DAΦNE NC cavity [with parameters V_g =250 kV, Q=3.3$\times 10^4$ (unloaded), R=2 Mohm, h=120, RF=368 MHz and I_b=5 A] uses both measures 1) and 2). Method 3) is somewhat specialist to the ARES cavity.

Mode-by-mode versus bunch-by-bunch feedback

See the "Review of Feedback Sytems" by K.Balewski 98 EPAC. A mode-by-mode feedback consists of many narrowband systems running in parallel, and is appropriate when modes are few and known. In the bunch-by-bunch approach the feedback for each bunch is computed using measurements of that bunch only. There is no need to have a-priori knowledge of which CB modes are present. The digital approach is versatile, flexible, economical, particularly with use of DSPs and digital filters. Very fast ADCs and DACs commercially available.

Transient compensation in LHC

Although injection and periodic transient beam-loading is still the dominant factor in the design of the LHC RF systems, plans have changed from the 95 "Yellow Book" description, Ref[1]. As consequence of the realization that bunch emittance and phasing will be inferior to values presumed in 1995, the scheme has grown to accomodate a greater effort in correcting injection/transfer errors, Refs[2-4].

Uncertainty of the LHC injection field due to "snap back" leads to energy errors up to 50 MeV. SPS-LHC synchronization will have a residual static error of $\approx 15^\circ$ at 400 MHz. Because of the long gap (70%), periodic transient beam-loading across the SPS batch (which is exacerbated[1] by the TW cavities) leads to a dynamical phase error from head to tail of the batch. A similar effect occurs in the LHC. However, one cannot arrange the cavity impedance in both machines so that effects are equal in SPS and LHC; hence there is a residual dynamical error. Furthermore, as additional SPS batches are added to LHC the transient voltage patterns will change regularly. The worst case error is anticipated to be $\approx 15^\circ$ at 400 MHz. Grossly simplified, the present strategy is to accept the 200 MHz SPS bunches into 200 MHz combined-capture-damper buckets in the LHC before adiabatic transformation to 400 MHz. We now describe the RF systems and how they will act.

SPS 200 MHz system

SPS (for LHC) will use four of the traditional 200 MHz Travelling Wave (TW) NC cavities (2 MV each) for acceleration, delivering bunches of emittance 1 eV.sec. Cavity voltage is reduced to 1 MV prior to extraction to better match aspect ratio of LHC 200 MHz buckets. Beam current RF component 1.2 A leads to significant beamload particularly at injection from the PS. A factor 10 reduction in beamload severity is accomplished by combination of feedback of V_g and feedforward of I_b.

LHC 400 MHz system

Driven by cost and impedance considerations LHC will use four (per beam) 400 MHz single-cell single-mode Super-Conducting (SC) cavities each capable of 2 MV/gap for acceleration. [An additional four cavity/beam is used to squeeze down the bunch length during collisions.] 400 MHz is the highest frequency compatible with longitudinal capture in LHC of the 200 MHz SPS bunches. The high stored energy of SC cavity reduces the effect of transient beamloading by an order of magnitude compared with a conventional Cu cavity. The wide bore of the cavity allows most HOMs to propagate down the beam-pipe to broadband damping antennae. The R/Q of HOMs is reduced to acceptable levels; and the fundamental is also reduced somewhat, which is beneficial for beam loading. Direct vector F/B of the gap voltage is used to further reduce the apparent impedance of the fundamental mode. Further, 1-turn delay feedback reduces the impedance at revolution harmonics. Because of the lengthy beam-gap, the cavities will be "half-angle detuned" to minimize power requirements. With these measures and Landau damping, few

[1]Whereas the generator fills the structure linearly with time, the beamload voltage rises quadratically.

CB-modes are anticipated and no bunch-by-bunch damper is envisioned. Note, the approach to HOMs and CB instability is much less aggressive than in e^+e^- B-factories.

LHC 200 MHz system

Four NC single-cell multi-mode 200 MHz cavities (based on a SW design used in the SPS) will be used to capture and damp the injected bunches. Two cavities are assigned per beam. 0.75 MV per cavity is used for acceptance and 25 kV is used for damping. SC cavities were rejected for lack of damping bandwidth. The cavity shape, with nose cones, is optimised for the accelerating mode resulting in $R_{\rm shunt} = 1.55$ Mohm and loaded Q=8000. By careful design, no HOMs fall on the major beam Fourier components (which are spaced at 40 MHz), so HOM loss is manageable. Antenna-type couplers are used to damp HOMs R<20/cavity and R/Q$\simeq 10$. Compensation of reactive beamloading is by half-angle detuning, as a compromise between batch and gap to minimize RF power. The cavities have direct vector feedback (gain=8) of the gap voltage, but this does not adequately combat the gap transients and so a 1-turn delay comb-filter feedback (gain of 32) further reduces the impedance at revolution harmonics.

Comb filter

The <u>ideal</u> comb filter has large gain at revolution harmonics, and small or zero gain elsewhere; it should also have 180° phase change across the the revolution line. (See discussion at 7th ICFA workshop.) Such a filter placed in the feedback path from voltage-output to generator-input reduces the cavity impedance precisely at the revolution harmonics, but the residual impedance at the upper and lower synchrotron sidebands (which belong to different CB mode numbers) should be no-zero and change sign so that both CB modes are damped. To accomplish zero impedance at the revolution harmonics, the generator has to deliver equal (but opposite signed) Fourier components to that of the beam; and this can entail significant power requirements. The comb functionality is naturally/automatically furnished by a loop with precisely 1-turn delay.

Injection scenario

The LHC 200 MHz cavities must damp the static m=0 mode phase error at injection and reduce the dynamical error across each batch to acceptable levels before filamentation causes significant longitudinal emittance increase. The LHC 400 MHz system is used to linearize the applied RF waveform, allowing the feedback to do useful work for up to 3000 turns. [1.5 and 0.325 MV is used in the 200 and 400 MHz systems, respectively.] In the subsequent 1000 turns, the 400 MHz is ramped to 8 MV/beam, and during a further 1000 turns, the 200 MHz capture system is ramped to zero. At this point, the 200 MHz generator delivers exactly the opposite of the beam current and so it is possible to introduce passive filters in the cavity which strongly reduce its impedance without affecting the amplifier operation.

Simulations

The LHC RF system has two sub-systems (200 and 400 MHz) operated under various conditions during different stages of an LHC fill. Due to the large beam current, both sub-systems strongly interact with the beam and are thus coupled together. A simulation program has been written by J. Tückmantel to evaluate in detail the behaviour of the LHC RF, Ref[2,5]. The program offers the possibility of runing "machine development studies" to examine many parameters and to find the best settings and the limits of the system.

Acknowledgement

The author wishes to thank J. Tuckmantel for permission to show a QuickTime movie of the LHC injection process, as excerpted from Ref[4].

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